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THEORY AND DESIGN OF ELECTRICAL ROTATING MACHINERY.(U)
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THEORY AND DESIGN OF ELECTRICAL

ROTATING MACHINERY

Annual Report for Period

Ending October 31, 1977

Submitted to

Office of Naval Research

in November 1977

Principal Investigator:

W. J. Carr, Jr.

Sponsored by:

Power Program ONR Contract No. N00014-72-C-0432

Identification NR097-385/12-5-72 (473)

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Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this program is to contribute toward new and improved rotating machines for Naval applications, with emphasis on superconducting machinery. Work has been performed on the theory of ac losses in multifilament superconductors and experiments were made to check the theory. A list of publications and abstracts of scientific papers published under the contract is given. Some work on the design of the iron circuit of a normal homopolar motor was concluded.

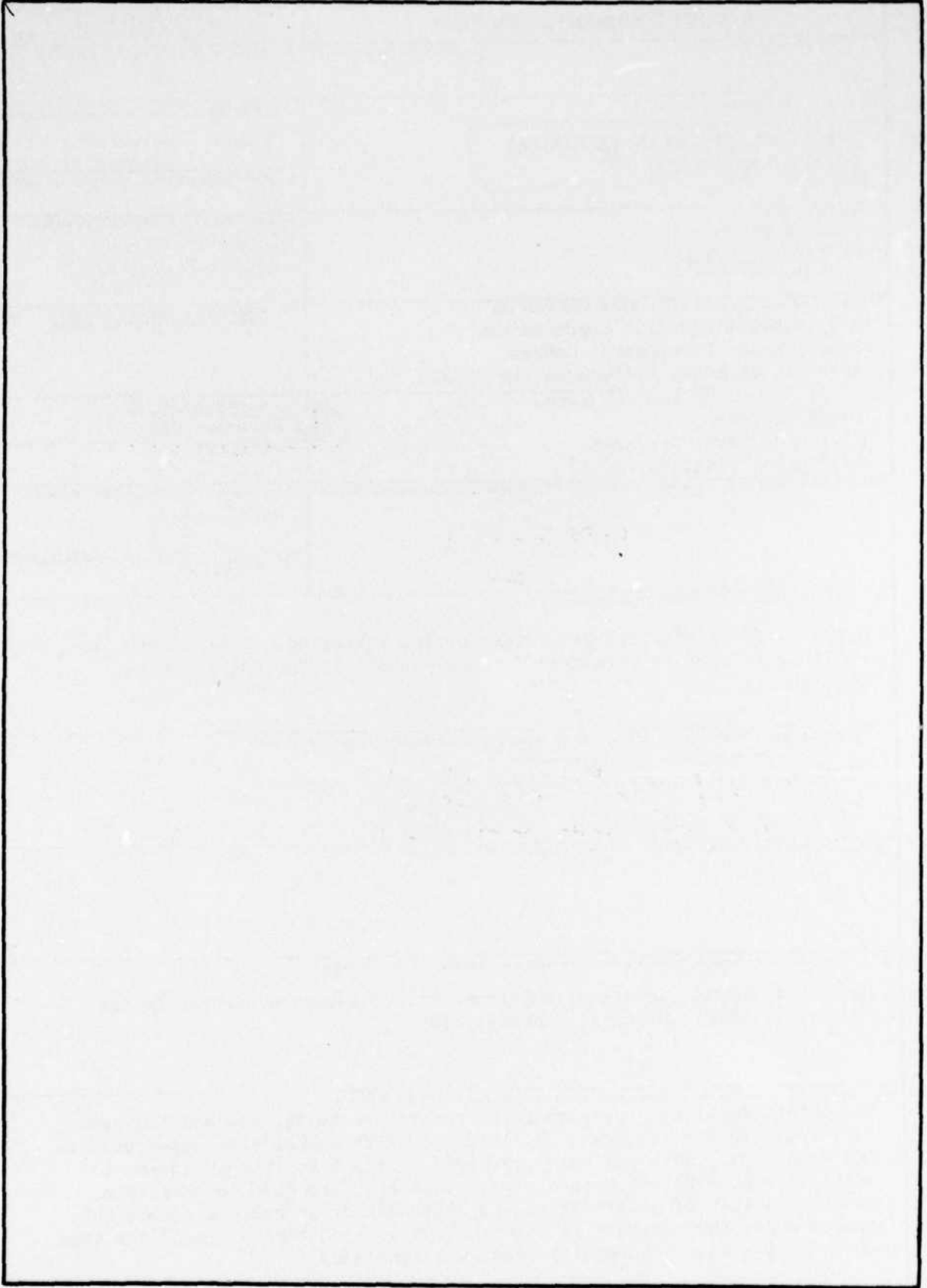DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE
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1.0 REPORTING PERIOD

This is the fifth annual technical report and covers the work
from November 1, 1976 to October 31, 1977.

2.0 OBJECTIVES

2.1 General

The objectives of the program are to contribute toward new and improved rotating machines for Naval applications, particularly in the area of superconducting machinery.

2.2 Specific

A specific objective was to study the ac loss which occurs in multifilament superconductors, with the object of providing the information needed for the design of stable low-loss conductors for use in rotating machines.

A smaller part of the program was used to investigate normal homopolar motors.

3.0 SUMMARY

This annual report is in the nature of a status report of unfinished tasks and a summary of technical publications made during the past year and during the life of the contract. Completed tasks have all been published, or are scheduled for publication in the scientific literature, and therefore are not discussed at length in this report. Abstracts of the work, and the Journal of Publications are listed at the end.

Approximately 90% of the funding on this program was spent in the study of ac losses in multifilament superconductors. This is a basic research program to study losses, with the primary objective of the program being an understanding of the various loss mechanisms, and the development of methods for accurately calculating losses under various conditions of possible interest in regard to superconducting rotating machines.

Although it is obvious from a study of the recent literature on ac losses that some problems still remain to be solved, even in the relatively simple cases of transverse and longitudinal fields in the absence of transport current, for the most part these losses are now understood. In particular considerable progress has been made under this contract in understanding longitudinal field losses during the past year. In addition some progress was made on the combined effects of transport current and applied magnetic fields. However, the latter is a large area of unfurnished work and demands the most attention in the future.

The work done on this project which was not directly connected with ac losses was connected with the theory of homopolar machines containing an iron path for the flux. A method for shaping the iron path was developed, which eliminates the necessity for a compensating winding to prevent circumferential saturation of the iron.

4.0 STUDIES OF AC LOSSES

Interest in ac loss theory and the need for more accurate cal-
culations from the standpoint of superconducting machinery design arises
in two ways: (1) where the ac loss is small and the interest is in the
proper amount of cooling needed to remove the heat and (2) where the ac
losses are large and form the primary design limitation. AC loss due to
ripples in a dc magnetic field and loss due to slow switching of the field
usually produce no problem if they are well understood and predictable,
so that adequate cooling can be provided for, and a proper conductor
design can be selected. The question here is reliability at minimum
cost. To obtain this information entirely from the construction and
testing of experimental machines would require too long a time period and
would be very expensive.

The second category is connected with the possibility of using
superconductors in a primarily ac field, and future hopes for revolution-
ary machine design. The rate of recent progress in conductor design, and
in the understanding of the various loss mechanisms which dictate a given
design, indicate the likelihood that superconductors can be developed for
fully ac applications. The attainment of this goal would open the possi-
bility of new designs and new types of superconducting machinery.

The work which has been done under this contract, to date, has
been mainly concerned with understanding the loss mechanisms due to a
transverse or a longitudinal applied magnetic field in the absence of
transport current in the conductor. The results may be used for the case
where the transport current is small, but not for the case where a trans-
port current that is an appreciable fraction of the critical current is
flowing in the conductor. A reasonably good understanding of these losses
has now been obtained, and for the most part measurements which have been
made agree rather closely with the calculations. During the past year

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some loss measurements have been reported in the literature which purport
to disagree with the theory. Some of these findings are simply the result
of not properly applying the theory to the special conditions which
exist. Other cases, however, seem to require a close look, to see if
some modification in the theory is required. In the case of longitudinal
field losses the general theory has been completed only during the past
year and not enough measurements are yet available to check the calcula-
tions.

Obviously before the theory is complete, an understanding of
the effect of transport current on the loss must be developed. An attack
on this problem was started during the past year but the work is far from
complete. The particular aspect which was investigated was the effect of
a dc transport current on the transverse field losses. The results were
reported at the CEC-ICMC Conference in Boulder, Colorado.

5.0 STUDIES ON HOMOPOLAR MOTORS

In a conventional homopolar motor or generator with an iron circuit for the magnetic flux, problems arise due to saturation of the iron in the circumferential direction, which decreases the useful flux across the air gap. This problem is generally solved by the use of a compensating winding. However the compensating winding adds to the copper loss and increases the effective air gap. A magnetic circuit design using optimized circumferential air gaps in the iron has been designed which avoids the necessity of a compensating winding. This work will be reported on at the next winter meeting of the IEEE Power Engineering Society.

6.0 PUBLICATIONS DURING THE PAST YEAR

1. W. J. Carr, Jr., "Longitudinal and Transverse Field Losses in Multi-
    filament Superconductors," IEEE Transactions on Magnetics, Vol. MAG-13,
    192 (1977).

Abstract: A review is given of the method of calculating losses
in a composite twisted multifilament superconductor based on the aniso-
tropic continuum model, and a summary of results are shown for the loss
as a function of frequency due to longitudinal and transverse applied
fields. In both cases three frequency ranges may be distinguished in
which (1) the magnetic field in the superconductor is just the applied
field, (2) the field produced by internal currents becomes important, and
(3) skin effect develops in the eddy currents, which flow transverse to
the filaments. In addition to these losses in the body of the supercon-
ductor (characterized by a vanishing component of electric field parallel
to the filament axes), the losses in the current saturated boundary layer
is described. Some discussion is also given on the use of ac field losses
in calculating the "ramped" field case.

2. W. J. Carr, Jr., "Longitudinal Field Losses in Multifilament Super-
    conductors over a Range of Frequencies," J. Appl. Phys., 2022 (1977).

Abstract: The power loss in a twisted multifilament supercon-
ductor due to a time-dependent longitudinal magnetic field is calculated
as a function of frequency. The longitudinal field is assumed to have a
sinusoidal dependence on both space and time, alternately changing direc-
tion along the conductor over a length ℓ. The eddy current loss, as a
function of frequency, initially is approximately proportional to ℓ^2 and
rises as the square of the frequency, until it reaches a plateau which
tends to be frequency independent and inversely proportional to ℓ^2.
After a further increase with frequency, the skin effect region is reached

with frequency to the one-half power dependence. The current-density distribution in the conductor is calculated, and it is shown that for large ℓ the entire cross section of the conductor can become current saturated if the amplitude of the ac field is greater than $L\lambda j_c$ where L is the twist length, j_c is the critical current density, and λ is the fraction of superconductor.

3. W. J. Carr, Jr., J. H. Murphy, and G. R. Wagner, "Alternating Field Losses in Filamentary Superconductor Carrying DC Transport Current," To appear in the Proceedings of the CEC-ICMC Meeting in Boulder, CO 1977.

Abstract: Alternating field losses in multifilament superconductors have been calculated previously only for special limiting cases, i.e., for the case of full field penetration of the filaments, or for the case of no transport current. From these limiting values interpolation formulas are given here for the full range of alternating field and dc transport current, assuming only that the frequency is below the critical frequencies for internal field effects, and that saturation effects in the outer filaments may be neglected. The results are compared with some measurements.

4. W. J. Carr, Jr., "Magnetic Circuit Design for a Homopolar Motor," Westinghouse Research Report 76-9C30-MACON-P2. Submitted to the Winter Meeting IEEE Power Engineering Society in New York, January 1978.

Abstract: The use of iron to enhance the flux density in a homopolar machine is limited by the presence of a large circumferential field which tends to saturate the iron in the wrong direction. It is shown that the use of an iron structure with optimized circumferential gaps can overcome this difficulty, and in many cases eliminate the necessity of a compensating current.

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7.0 COMPLETE LIST OF PUBLICATIONS UNDER THE CONTRACT

1. W. J. Carr, Jr., "AC Loss in a Twisted Filamentary Superconducting Wire," Journal of Applied Physics, 45:929 (1974).

Abstract: Calculations are made for the ac losses in a twisted filamentary superconductor by assuming a continuum model with anisotropic conductivity. The Maxwell equations are solved for a long wire of radius R_0 and twist length L. In terms of the classical skin depth δ, appropriate for the conductivity perpendicular to the filaments, the losses are calculated for an applied magnetic field transverse to the wire axis in the case of (1) a uniform field ($\sqrt{2} R_0/\delta < < 1$, $L/2\pi\delta < < 1$), (2) shielding from surface currents ($\sqrt{2} R_0/\delta < < 1$, $L/2\pi\delta > > 1$), and (3) skin effect ($\sqrt{2} R_0/\delta > > 1$). Losses are also calculated for the case of a transport current in no applied field. The model can be used in more general cases and has the virtue of giving precise results with a minimum of auxiliary postulates.

2. W. J. Carr, Jr., "AC Loss in a Twisted Filamentary Superconducting Wire II," Journal of Applied Physics, 45:935 (1974).

Abstract: Hysteresis losses in a twisted filamentary superconducting wire are calculated for various cases corresponding to complete penetration of the magnetic field into the wire, shielding of the field by the supercurrents, and shielding due to eddy currents. In general, the wire may be divided into two regions: an outer saturated layer which tends to behave at the higher frequencies like a solid superconductor, and the interior where the average parallel electric field vanishes and the wire behaves like a collection of individual filaments.

3. J. H. Murphy, M. S. Walker, and W. J. Carr, Jr., "Theory of Alternating Field Losses in Cylindrical Twisted Multifilamentary Superconductors," Intermag Conf. Proc., IEEE Trans. Mag., 10:868 (1974).

Abstract: The theory of sinusoidal alternating field losses in a cylindrical multifilamentary superconducting wire is discussed. Hysteresis loss expressions are presented for the individual filament losses in the interior of the wire when these filaments are completely penetrated, and for the loss occurring in an outer current-saturated layer of the wire. The loss expressions presented were determined assuming a continuum model with anisotropic conductivity for the superconductor. The case of a permeability different from unity, applicable for weak fields, is discussed.

4. W. J. Carr, Jr., "Electromagnetic Theory for Filamentary Superconductors," Physical Review B, 11:1547 (1975).

Abstract: It is shown that a multifilament superconductor, made up of a bundle of twisted filaments embedded in a normal matrix, can be treated as a new state of matter with anisotropic electrical and magnetic properties. Macroscopic electromagnetic field vectors, which satisfy Maxwell's equations, are defined in terms of averages over the "microscopic" fields. However, the sources for the field, i.e., the current and charge densities and the magnetization and polarization, differ in some respects from those for ordinary matter. In particular, since the elementary magnetic dipole moments are distributed along lines rather than located at fixed points, the definition of the magnetization transverse to the filaments differs by a factor of 2 from that for ordinary matter, and the definition of the macroscopic current density is also slightly modified. Constitutive relationships among the field vectors in terms of permeabilities, dielectric constants, and conductivities are examined in the limits of strong and weak fields.

5. W. J. Carr, Jr., "Conductivity, Permeability and Dielectric Constant
    in a Multifilament Superconductor," Journal of Applied Physics,
    46:4043 (1975).

Abstract: Results are given for the permeability, conductivity,
and dielectric constant of a multifilament superconductor, treated as an
anisotropic state of matter. The calculations are made for the limiting
cases of strong and weak ac magnetic fields compared with the field re-
quired for complete penetration of the filaments. General expressions
are given for the ac power loss.

6. W. J. Carr, Jr., M. S. Walker, and J. H. Murphy, "Alternating Field
    Loss in a Multifilament Superconducting Wire for Weak AC Fields
    Superposed on a Constant Bias," Journal of Applied Physics, 46:4048
    (1975).

Abstract: Expressions are given for the alternating field loss
in a twisted filamentary superconductor as a function of frequency and
magnetic field, for the case of small ac applied fields which do not com-
pletely penetrate the filaments. The ac field is superimposed on a fixed
bias field. In this limit the effective diamagnetism of the filament
leads to a permeability less than unity for the composite. Expressions
are presented for both the hysteresis and the eddy current loss.

7. M. S. Walker, W. J. Carr, Jr., and J. H. Murphy, "Loss Behavior in
    Twisted Filamentary Superconductors," IEEE Trans. on Magnetics,
    MAG-11, 1475 (1975).

Abstract: A careful comparison between theory and experiment
is made for the transverse alternating field eddy current losses in three
twisted mixed-matrix filamentary superconductors of the composition
3CuNi:3Cu:1NbTi. The measurements were made over a wide frequency range,
up to 10^6 Hz. Good agreement is obtained.

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8. W. J. Carr, Jr., "Possibility for an All-Superconducting Synchronous Motor or Generator," Westinghouse Research Report 73-9J2-MACON-R1.

    Abstract: Possibilities for a motor or generator with super-conducting armature and field winding are discussed, and the ac losses that would be expected in the armature winding are calculated.

9. W. J. Carr, Jr., "Design Theory for a Fully Superconducting Synchronous Motor or Generator," Westinghouse Research Report 73-9J2-MACON-R2.

    Abstract: Theory is developed for a superconducting synchronous motor or generator having both the field and the armature windings superconducting. An approximate design is given for a four-pole 30 MW operating at 180 rpm.

10. J. H. Murphy and W. J. Carr, Jr., "Eddy Current Losses in Twisted Multifilamentary Superconductors," Westinghouse Research Report 73-9J2-MACON-R3.

    Abstract: Calculations are made for the eddy current losses in a multifilament superconductor having a copper sheath.

11. L. N. Wedman, "A Low Speed Direct Current Superconducting Heteropolar Motor," Report EM4562.

    Abstract: Important progress in assessing the limits of ratings for new concept electrical machines for ship propulsion applications has been achieved. The superconducting heteropolar motor has been identified as the most promising machine concept for slow-speed, high-power use. Maximum utilization of the drum homopolar machine is limited by transmission line current ratings, and may be greatly improved if an in-line drive is required, thus allowing the use of the homopolar torque converter. The magnetic disc homopolar motor with water cooling appears to be the preferred concept for low-speed homopolar motor applications. Technical progress in the conceptual configuration of the superconducting

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heteropolar machine is presented, together with a report on progress on the solution of commutation problems in such machines.

12. W. J. Carr, Jr., M. S. Walker, D. W. Deis, and J. H. Murphy, "Hysteresis Loss in a Multifilament Superconductor," Advances in Cryogenic Engineering, 22, 428 (1977).

Abstract: Theory of hysteresis loss in a multifilament superconductor is reviewed and measurements are presented for a mixed-matrix NbTi conductor. The measurements were made calorimetrically as a function of frequency and transverse ac magnetic field, for a 50 kOe dc bias field, and also with no bias. Both a linear ac field dependence and a cubic field dependence were observed, corresponding to the case of complete penetration of the filaments, and partial penetration. Comparison of experiment with calculation was made by evaluating the critical current density from the measurements and the loss expression, and comparing this value with a direct measurement of j_c from transport current. Good agreement was obtained.

13. W. J. Carr, Jr., "Parallel Field Losses in Twisted Multifilament Superconductors," Sixth Symposium on Engineering Problems of Fusion Research, IEEE Pub. No. 75CH1097-5-NPS (1975), p. 152.

Abstract: In some applications of multifilament superconducting wire an appreciable component of a time dependent magnetic field exists along the twisted filaments, and across the matrix, and loss and stability problems are introduced. It has been suggested by various authors that these effects can be minimized by periodically introducing reverse twist in the wire. A calculation is given for the eddy current loss that can be expected for such a conductor. The calculation also applies for the case where the twist is uniform but the direction of the magnetic field reverses along the length of the conductor.

14. W. J. Carr, Jr., "Longitudinal and Transverse Field Losses in Multi-filament Superconductors," IEEE Transactions on Magnetics, Vol. MAG-13, 192 (1977).

Abstract: A review is given of the method of calculating losses in a composite twisted multifilament superconductor based on the aniso-tropic continuum model, and a summary of results are shown for the loss as a function of frequency due to longitudinal and transverse applied fields. In both cases three frequency ranges may be distinguished in which (1) the magnetic field in the superconductor is just the applied field, (2) the field produced by internal currents becomes important, and (3) skin effect develops in the eddy currents, which flow transverse to the filaments. In addition to these losses in the body of the superconductor (characterized by a vanishing component of electric field parallel to the filament axes), the losses in the current saturated boundary layer is described. Some discussion is also given on the use of ac field losses in calculating the "ramped" field case.

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8.0 PROGRAM PERSONNEL

The personnel who have contributed to this program are as follows:

W. J. Carr, Jr. - Consultant in Magnetics and Superconductivity

J. H. Murphy   - Engineer, Cryogenics

G. R. Wagner   - Physicist, Cryogenics.

Consultation has been provided by other members of the Machinery and Cryogenics Groups.

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